

REQ. NO. 2-9133

DRAFT NOT FOR PUBLICATION
SUBJECT TO FINAL REVISION AND
ADDITIVES.

CONTRACT REPORT NO. OSQ 82-00165

DEVELOPMENT OF HIGH STRENGTH FLY ASH/PORTLAND
CEMENT CONCRETE FOR PRECAST INDUSTRY

BY

M. Plumet, V. De Benedictis and C. Bédard

of

Canada Cement Lafarge Limited

Work on this project was conducted under the auspices
of Canada Centre for Mineral and Energy
Technology, Energy, Mines and Resources, Canada

DSS FILE NUMBER: 23SQ.23440-2-9133

CANMET PROJECT NUMBER: 410 014 NEP

CANMET SCIENTIFIC AUTHORITY: V.M. Malhotra

MICROMEDIA

DEC 27 1983

26pp

DEVELOPMENT OF HIGH-STRENGTH FLY ASH/PORTLAND
CEMENT CONCRETE FOR PRECAST INDUSTRY

by

M. Plumat, Director, Centre de recherches appliquées de Canfarge

V. De Benedictis, Assistant-Director, Centre de recherches appliquées de Canfarge

C. Bédard, Project Manager, Centre de recherches appliquées de Canfarge

ABSTRACT

This paper reports results of an investigation performed to develop high-strength concrete incorporating increasing amounts of fly ash as an addition to high early strength, (type 30), Portland cement. Three water-to-cement ratios were used: 0.45, 0.40 and 0.35. The reference mixes had no fly ash while the fly ash/Portland cement concrete contained 20%, 30% and 40% of fly ash by weight of cement. The cement dosage was kept constant at 370 kg/m³.

The fly ash was used as partial replacement of the fine aggregate. A superplasticizer was used to maintain the slump at $21\frac{1}{2} \pm \frac{1}{2}$ inch while an air-entraining agent kept the air content within the desired level of $4.5 \pm 1.0\%$.

The results show that the incorporation of fly ash was not accompanied by a significant increase in the 1 day compressive strengths of the concrete when cured at room temperature ($23^{\circ}\text{C} \pm 2^{\circ}$). At this temperature the fly ash reacts much too slowly and begins to improve the overall properties of concrete at the later age of 28 days.

In order to accelerate the anticipated benefits of fly ash on the early strength of concrete, we would suggest to further this study to include heat curing of the concrete as is commonly practiced by the precast industry.

TABLE OF CONTENTS

	Pages
ABSTRACT	i
INTRODUCTION	1
SCOPE OF INVESTIGATION	2
MATERIALS USED	2
- Cement and fly ash	2
- Aggregates	2
- Air entraining agent	2
- Superplasticizer	3
CONCRETE MIXES	3
PREPARATION AND CASTING OF SPECIMENS	3
TESTING OF SPECIMENS	4
TEST RESULTS	4
DISCUSSION OF TEST RESULTS	5
- Mix proportionning	5
- Fresh concrete	5
- Compressive strength and modulus of elasticity	5
- Flexural strength and splitting tensile strength	5
- Freeze thaw	6
- Air void system	6
CONCLUDING REMARKS	7
ACKNOWLEDGEMENT	7
REFERENCES	8

LIST OF TABLES

	Page
No. 1 Physical properties and chemical analysis of CSA type 30 (ASTM type 3) Cement.	9
No. 2 Physical properties and chemical analysis of the fly ash.	10
No. 3 Project outline.	11
No. 4 Proportions and properties of fresh concretes.	12
No. 5 Number of test specimens cast and tested from each batch.	14
No. 6 Properties of hardened concrete.	15
No. 7 Properties of hardened concrete-air void system.	17
No. 8 Compressive strength - f'_c .	18
No. 9 Modulus of elasticity at 28-days.	19
No. 10 Splitting tensile strength at 28-days.	19
No. 11 Flexural strength at 14-days.	19

LIST OF FIGURES

No. 1a Compressive strength as % of reference at 1 and 7 days versus the fly ash content.	20
1b Compressive strength as % of reference at 28 and 91 days versus the fly ash content.	21
No. 2 Compressive strength versus the water-to-cement ratio.	22

INTRODUCTION

The use of mineral products in concrete can contribute to the conservation of both energy and resources.

One such material is fly ash, a by-product from the combustion of pulverised coal in thermal power stations.

Fly ash is being incorporated increasingly in concrete at batch plant for cast in place construction, however, its use in precast concrete to replace cement as fine aggregate is relatively unknown in Canada.

In 1981 CANMET reported investigation on the «Development of High Strength Concrete incorporating a large percentage of fly ash and superplasticizers» and indicated possible uses of fly ash in precast concrete industry.

This investigation is a follow up of the one reported by CANMET in 1981 and reports the performance of concrete incorporating up to 40% fly ash from an Alberta source.

This study was undertaken by Canada Cement Lafarge Ltd. under DSS Contract No. 23SQ-23440-2-9133 from CANMET, Energy, Mines and Resources, Canada and is a part of CANMET project No. 360465, entitled «Performance and durability of concrete incorporating waste material».

SCOPE OF INVESTIGATION

The test program consisted of an evaluation of high-strength air-entrained concrete containing type 30 Portland cement and four fly ash contents (0%, 20%, 30% and 40% by weight of cement) in combination with two commercially available admixtures (a superplasticizer and an air entraining agent). The following series of concrete mixes were made.

i) Program A - reference mixes -

To determine the mechanical properties of concrete made with three water-to-cement ratios: 0.45, 0.40 and 0.35.

ii) Program B - fly ash mixes -

To determine the mechanical properties of concrete made by adding 20%, 30% and 40% of fly ash to the reference mixes above. The fly ash replaces part of the fine aggregate.

MATERIALS USED

Cement and fly ash

CSA type 30 high early strength cement (ASTM type 3) and a Western Canada fly ash meeting the requirements of ASTM standard C 618 for a class C fly ash were used. The physical properties and chemical analysis of the cement and fly ash are given in table 1 and 2 respectively.

Aggregates

Graded crushed limestone of 20mm maximum size was used as coarse aggregate and natural sand was used as the fine aggregate. The relative densities of both the coarse and fine aggregate was 2.70, the absorption values were respectively 0.5 and 0.7 (CSA Can 3 - A23.2; 6A and 12A).

Air entraining agent

The air entraining agent used in the concrete mixes was a sulphonated hydrocarbon type.

Superplasticizer

A superplasticizer sulphonated naphtalene formaldehyde condensate type was used in the concrete mixes. They are usually available as 42% aqueous solution with a density of 1,20 and are dark brown. The chloride content is negligible.

CONCRETE MIXES

Altogether, there were 12 mix series as presented in the project outline of table 3. The Portland cement content (Type 30) was kept constant at 370 kg/m³. The three reference mixes (A1, A2, A3) had no fly ash and water-to-cement ratios of 0.45, 0.40 and 0.35 respectively. We then repeated this W/C sequence with three different fly ash contents 20% (B1, B2, B3), 30% (B4, B5, B6) and 40% (B7, B8, B9). The fly ash replaced part of the fine aggregate. The slump was maintained the same throughout the project by the use of a superplasticizer while the air content was controlled through the use of an air entraining agent.

The mixing procedure was as follows: the coarse and fine aggregate, the cement, the fly ash (where used) and the water together with the air air-entraining agent were placed in a pan mixer of 0.06m³ capacity and first mixed for one minute. The mixing was continued and the superplasticizer (where used) was added during the next 2 1/2 minutes.

The properties of the fresh concrete, i.e. slump, density and air content were determined immediately after mixing, (Table 4). The concrete one day density was measured after demoulding.

PREPARATION AND CASTING OF SPECIMENS

There were twelve different concrete mixes, A1 to A3 without fly ash and B1 to B9 with growing amounts of fly ash. Each mix series consisted of four identical batches mixed consecutively. Test cylinders, 150 x 300mm (6 x 12 in.) and prisms 75 x 75 x 350mm (3 x 3 x 14 in.) were cast. The details of the specimens cast are given in Table 5. The cylinder specimens were compacted by the standard rodding procedure and cast in cardboard moulds. The prisms were compacted by vibration and cast in steel moulds.

All the specimens were covered with a polyethylene sheet and left in the mixing room maintained at $23 \pm 2^{\circ}\text{C}$ and about 50% relative humidity for 24 hours. They were then demoulded and transferred to a standard moist-curing room until required for testing.

TESTING OF SPECIMENS

The cylinder and prism specimens were tested in accordance with the schedule shown in Table 5. The test cylinders for compressive strength and for modulus of elasticity were capped with a sulphur capping compound on both ends and tested in accordance with CAN 3 - A23.2 - 9C (ASTM C39) for compressive strength and ASTM C469 to determine the chord modulus of elasticity. The test cylinders for splitting tensile strength were tested according to CAN3 - A23.2 - 13C (ASTM C496). The test prisms for flexural strength were tested according to CAN 3 - A 23.2 - 8C (ASTM C78) using simple beam with third-point loading. The prism specimens for freeze thaw were tested according to ASTM C 666, Procedure A, for rapid freezing and thawing in water. The prism specimens for air void content of hardened concrete were tested according to ASTM C457 by microscopical determination.

TEST RESULTS

The strength tests results, modulus of elasticity, durability factor and air void system for each batch are given in tables 6 and 7. The strength test results and modulus of elasticity are further sorted by water-to-cement ratio and fly ash content in tables 8 to 11. Plots of the compressive strength (expressed in percent of the reference mix A1 at $W/C = 0.45$) versus the fly ash content is shown in figure 1a and 1b, while the compressive strength versus the W/C ratio is shown in figure 2.

DISCUSSION OF TEST RESULTS

Mix proportioning

Fly ash was introduced in additions of 20%, 30% and 40% by weight of cement to the reference mixes to compare the concrete properties of mixes with and without fly ash at three different W/C ratios which were 0.45, 0.40 and 0.35.

Fresh concrete

The workability of the mixes was satisfactory. However, at high dosages of superplasticizer the concrete became sticky. The quantity of superplasticizer used to maintain equivalent slumps throughout the mix series ranged from 0% to 2.35% by weight of cement. The demand for high-range-water-reducer increases as the water content decreased. It was also necessary to increase the amount of air-entraining agent to maintain the air content at $4.5\% \pm 1$. The dosage used throughout the 12 mix series ranged between 150 mL to 900 mL per cubic meter of concrete.

Compressive strength and modulus of elasticity

Increases in the compressive strength and in the modulus of elasticity up to 28 days can be attributed to the reduced W/C ratios. The addition of fly ash at the constant cement dosage of 370 kg/m^3 seems to produce no incremental effect on the compressive strength at 1 and 7 days as can be seen in figure 1a. The 28-day results show a slight increase of approximately 5% for both f'c and modulus of elasticity at the higher W/C ratio of 0.45, while the lower W/C ratios of 0.40 and 0.35 appear unaffected by the addition of fly ash. Compressive strength at 28 days versus the W/C in figure 2 indicates that the compressive strength of both fly ash and non-fly ash mixes obey the W/C ratio rule. On the other hand as shown in figure 1b, the 91-day results show a net increase in the compressive strength of the concretes containing fly ash. This gain in strength increases as the fly ash content increases. These results indicate that the beneficial pouzzolanic action of fly ash in concrete occurs at later ages when the concrete is cured at room temperature.

Flexural strength and Splitting tensile strength

The results obtained on flexural strength and splitting tensile strength further substantiate the late reaction and contribution of fly ash to the properties of concrete. The 14-day flexural strengths of the concretes containing fly ash show no improvement over the reference concrete. The 28-day splitting tensile strength show a slight amelioration for the fly ash concrete mixes.

Freeze -thaw

For the higher fly ash content mixes slight deterioration on the surface of the prisms was observed after a few cycles of freezing and thawing. This is probably due to water washing off the unreacted fly ash fines at early ages. Nevertheless, durability factors for fly ash mixes are equal or higher than the non-fly ash mixes after freezing and thawing in water for 300 cycles.

Air void system

The air contents of the hardened concrete prisms are consistently lower than the corresponding values obtained for the plastic concretes (from 1.4 to 3.5% for hardened concretes against 3.5 to 5.2% for plastic concretes, tables 7 and 4).

This is due to the loss of air during vibration of the prisms to ensure the proper compaction. The air contents reported in hardened concretes are judged to be mainly entrapped air. However, the low w/c ratios of the concretes provide adequate freeze-thaw resistance as we have seen in the section above.

It was also noticed that as the fly ash content increased, the spacing factor was shortened and the specific surface area increased rapidly to unusually high values. This might be explained by the fact that many unhydrated fly ash glass spheres would fall off during polishing of the specimens and created a large number of tiny air voids.

CONCLUDING REMARKS

It is possible to produce high strength concrete with a constant cement content (type 30) of 370 kg/m³ and incorporating additions of fly ash up to 40% by weight of cement without affecting the mechanical properties of concrete at early ages (1 and 7 days). The benefits of fly ash are not felt until 28 days when the concrete is cured at room temperature ($23 \pm 2^{\circ}\text{C}$). At this temperature the fly ash reacts much too slowly to be of interest to the precast industry.

To accelerate the benefits to be obtained from the use of fly ash on the early strength of concrete, we would suggest to further this study to include heat curing of the concrete at elevated temperatures as is commonly practiced by the precast industry. In this manner, we may be able to demonstrate the beneficial use of this low energy product in the production of high early strength concrete.

ACKNOWLEDGEMENT

Financial support for this study was provided by CANMET to Canada Cement Lafarge Ltd. under Contract No. 23SQ.23440-2-9133.

CANMET Scientific Authority was: V.M. Malhotra, P. Eng., Head of Construction Materials Section Industrial Minerals Laboratory.

Principal investigators at Canada Cement Lafarge Ltd. were:
Marc Plumat, ing., Director R. and D. Centre
Vito De Benedictis, B.Sc., Assistant-director, R. and D. Centre
Claude Bédard, ing., M. Sc.A., Project Manager, R. and D. Centre

References

1. Gebler, S.H., «The effects of high-range water reducers on the properties of freshly mixed and hardened flowing concrete.» (RD 081.01T), Portland Cement Association, 1982, 12 p.
2. Mukherjee, P.K., Loughborough, M.T. and V.M. Malhotra, «Development of high-strength concrete incorporating a large percentage of fly ash and superplasticizers»; CANMET report 81-124; Energy, Mines and Resources Canada, Ottawa, August 1981, 18 p.
3. Neville, A.M., «Properties of CONCRETE», third edition, Pitman Publishing limited, London, 1981.

TABLE 1 - PHYSICAL PROPERTIES AND CHEMICAL ANALYSIS OF CSA TYPE 30 (ASTM TYPE 3) CEMENT

Description of Test	CSA Type 30 Cement
<u>Physical tests - general</u>	
Time of set (vicat needle), h:min	1:20
Fineness: 45um (passing), %	96.8
Surface area (Blaine), m ² /kg	550
Soundness (autoclave), %	0.03
<u>Physical tests - mortar strength</u>	
Compressive strength of 51-mm cubes, MPa	
1-day	25.0
3-days	35.2
28-days	47.9
<u>Chemical analysis, %</u>	
Insoluble residue	0.6
Silicon dioxide (SiO ₂)	20.2
Aluminum oxide (Al ₂ O ₃)	4.8
Ferric oxide (Fe ₂ O ₃)	2.7
Calcium oxide (CaO), total	61.9
Magnesium oxide (MgO)	2.5
Sulphur trioxide (SO ₃)	4.3
Loss on ignition	1.9
Other	1.8
<u>Compound composition, %</u>	
Tricalcium silicate (C ₃ S)	47.5
Dicalcium silicate (C ₂ S)	20.4
Tricalcium aluminate (C ₃ A)	9.1
Tetracalcium aluminoferrite (C ₄ AF)	8.3

TABLE 2 - PHYSICAL PROPERTIES AND CHEMICAL ANALYSIS OF THE FLY ASH

Description of test	Specification Requirements		Test Results
	ASTM C618-78	CSA 266.3M	
<u>Physical Tests</u>			
Relative density	-	-	2.11
Pozzolanic activity index with portland cement	min 75	min 75	86
Soundness, autoclave expansion or contraction, %	max 0.5	max 0.5	0.00
Amount retained when wet sieved on 45 um sieve, max %	max 34	max 34	17.8
Multiple factor (product of L.O.I. and fineness, amount retained when wet sieved on 45 um sieve), max %	max 225	max 225	7.1
<u>Chemical Tests</u>			
Silicon dioxide (SiO ₂) + aluminum oxide (Al ₂ O ₃) + iron oxide (Fe ₂ O ₃), %	min 70.0	-	81.5
Sulphur trioxide (SO ₃), %	max 3.0	max 3.0	0.3
Available alkalies as Na ₂ O, %	max 1.5	max 2.5	2.2
Loss on ignition, %	max 12.0	max 12.0	0.4

TABLE 3 - PROJECT OUTLINE .

Fly ash Content (% by cement wt) \ W/C	0.45	0.40	0.35
0	A1	A2	A3
20	B1	B2	B3
30	B4	B5	B6
40	B7	B8	B9

TABLE 4 - PROPORTIONS AND PROPERTIES OF FRESH CONCRETE

Mix No.	Batch No.	Mix proportions, kg/m ³					W/C	W/(Cement + Fly Ash)	Superplasticizer % by cement weight	Properties of Fresh Concrete			Concrete Dry Density, kg/m ³
		CSA Type 30 Cement	Fly Ash	Fine Aggregate	Coarse Aggregate	Total Water				Slump, mm	Air, %	Unit Weight, kg/m ³	
A1	1	371	-	820	1030	169	0.46	0.46	-	75	3.5	2390	2310
	2	371	-	820	1030	169	0.46	0.46	-	75	4.0	2390	
	3	371	-	820	1030	169	0.46	0.46	-	70	4.0	2390	
	4	371	-	820	1030	169	0.46	0.46	-	80	4.0	2390	
A2	1	379	-	840	1050	153	0.40	0.40	0.94	70	3.8	2420	2370
	2	379	-	840	1050	153	0.40	0.40	0.94	65	3.8	2420	
	3	377	-	835	1045	153	0.41	0.41	0.94	55	4.1	2410	
	4	375	-	830	1040	152	0.40	0.40	0.94	65	4.2	2400	
A3	1	381	-	845	1055	137	0.36	0.36	1.40	75	4.3	2420	2390
	2	381	-	845	1055	137	0.36	0.36	1.40	70	4.3	2420	
	3	383	-	850	1060	137	0.36	0.36	1.40	55	4.5	2430	
	4	381	-	845	1055	137	0.36	0.36	1.40	55	4.2	2420	
B1	1	369	74	730	1040	167	0.45	0.38	0.26	75	3.7	2380	2310
	2	369	74	730	1040	167	0.45	0.38	0.26	75	3.8	2380	
	3	370	74	730	1045	167	0.45	0.38	0.26	75	3.7	2390	
	4	368	73	725	1040	167	0.45	0.38	0.26	75	4.2	2370	
B2	1	374	74	735	1055	151	0.40	0.34	0.78	75	3.7	2390	2340
	2	374	74	735	1055	151	0.40	0.34	0.78	65	3.7	2390	
	3	374	74	735	1055	151	0.40	0.34	0.78	65	3.7	2390	
	4	374	74	735	1055	151	0.40	0.34	0.78	65	3.7	2390	
B3	1	378	76	745	1070	136	0.36	0.30	1.60	75	4.0	2410	2370
	2	375	75	740	1060	135	0.36	0.30	1.60	70	4.3	2390	
	3	378	76	745	1070	136	0.36	0.30	1.60	70	4.2	2410	
	4	377	75	745	1065	135	0.36	0.30	1.60	70	4.0	2400	

TABLE 4 CONT'D - PROPORTIONS AND PROPERTIES OF FRESH CONCRETE

Mix No.	Batch No.	Mix Proportions, kg/m ³					W/C	W/(Cement + Fly Ash)	Superplasticizer % by Cement Weight	Properties of Fresh Concrete			Concrete Dry Density, kg/m ³
		CSA Type 30 Cement	Fly Ash	Fine Aggregate	Coarse Aggregate	Total Water				Slump, mm	Air, %	Unit Weight, kg/m ³	
B4	1	369	111	680	1045	167	0.45	0.35	0.58	80	3.7	2370	2310
	2	367	111	675	1040	167	0.45	0.35	0.38	80	4.0	2360	
	3	367	111	675	1040	167	0.45	0.35	0.58	75	4.0	2360	
	4	367	111	675	1040	167	0.45	0.35	0.58	75	4.1	2360	
B5	1	373	113	685	1065	152	0.41	0.31	1.10	65	3.5	2390	2330
	2	372	112	685	1060	151	0.41	0.31	1.10	60	3.7	2380	
	3	372	112	685	1060	151	0.41	0.31	1.10	65	3.7	2380	
	4	373	113	685	1065	152	0.41	0.31	1.10	70	3.9	2390	
B6	1	373	113	685	1065	134	0.36	0.28	1.54	70	5.0	2370	2330
	2	373	113	685	1065	134	0.36	0.28	1.54	80	5.2	2370	
	3	373	113	685	1065	134	0.36	0.28	1.54	70	4.8	2370	
	4	373	113	685	1065	134	0.36	0.28	1.54	80	5.3	2370	
B7	1	363	145	620	1050	164	0.45	0.32	0.39	75	4.3	2340	2290
	2	363	145	620	1050	164	0.45	0.32	0.39	80	4.2	2340	
	3	363	145	620	1050	164	0.45	0.32	0.39	75	4.2	2340	
	4	363	145	620	1050	164	0.45	0.32	0.39	80	4.2	2340	
B8	1	367	147	625	1060	149	0.41	0.29	1.09	70	4.3	2350	2290
	2	368	147	625	1065	150	0.41	0.29	1.09	70	4.2	2360	
	3	365	146	620	1055	149	0.41	0.29	1.09	75	4.4	2340	
	4	365	146	620	1755	149	0.41	0.29	1.09	70	4.4	2340	
B9	1	375	150	640	1085	136	0.36	0.26	2.35	65	4.4	2390	2335
	2	375	150	640	1085	136	0.36	0.26	2.35	80	4.5	2390	
	3	374	150	635	1080	136	0.36	0.26	2.35	70	4.4	2380	
	4	372	149	635	1075	136	0.36	0.26	2.35	80	4.5	2370	

TABLE 5 - NUMBER OF TEST SPECIMENS CAST AND TESTED FROM EACH BATCH.

Tests	Batch number			
	1	2	3	4
No. of cylinders for compression tests at				
1 - day	-	1	1	1
7 - days	-	1	1	1
28 - days	3	1	1	1
91 - days	-	1	1	1
No. of cylinders for 28-day splitting tensile test	1	1	1	1
No. of cylinders for 28-day modulus of elasticity	1	1	1	1
No. of prisms for 14-day flexural test	2	-	-	-
No. of prisms kept in moist curing room	2	-	-	-
No. of prisms for freeze thaw	2	-	-	-
No. of prisms for air void system	2	-	-	-

TABLE 6 - PROPERTIES OF HARDENED CONCRETE

Mix no.	Batch no.	W/C	Fly ash, % by wt. of cement	Properties of hardened concrete								Durability factor, % (Number of cycles)
				Compressive strength, MPa				Splitting Tensile strength, MPa	Flexural strength, MPa (2)	Modulus of elasticity, GPa		
				1-d	7-d	28-d	91-d					
A1	1	0.46	-	-	-	41.4 (1)	-	2.6	4.9	33.7	97.6 (314)	
	2	0.46	-	22.5	31.4	37.8	44.2	2.8	-	32.9		
	3	0.46	-	23.3	32.2	39.3	45.5	2.6	-	34.3		
	4	0.46	-	23.0	32.6	40.3	46.9	2.7	-	34.0		
A2	1	0.40	-	-	-	47.4 (1)	-	3.3	5.7	37.0	97.4 (307)	
	2	0.40	-	27.4	39.3	48.1	53.5	3.0	-	37.0		
	3	0.41	-	30.9	37.9	43.3	52.4	3.2	-	-		
	4	0.40	-	29.3	40.0	45.8	50.8	3.2	-	36.6		
A3	1	0.36	-	-	-	54.8 (1)	-	4.3	6.9	38.6	99.2 (301)	
	2	0.36	-	36.0	45.0	53.0	62.0	3.4	-	38.0		
	3	0.36	-	34.5	44.1	53.5	59.2	3.2	-	38.6		
	4	0.36	-	34.4	46.4	55.6	62.1	3.1	-	38.4		
B1	1	0.45	20.1	-	-	40.6 (1)	-	2.9	5.0	35.8	102.5 (320)	
	2	0.45	20.1	25.0	33.9	42.5	48.6	3.1	-	35.4		
	3	0.45	20.0	24.2	33.4	41.4	49.3	3.1	-	35.4		
	4	0.45	19.9	22.2	33.3	41.5	49.0	2.6	-	34.2		
B2	1	0.40	19.8	-	-	45.5 (1)	-	3.1	4.8	37.4	103.2 (313)	
	2	0.40	19.8	28.7	36.6	44.1	54.2	3.4	-	38.2		
	3	0.40	19.8	28.5	36.6	45.7	51.3	3.1	-	37.6		
	4	0.40*	19.8	27.5	36.6	45.7	53.0	2.7	-	36.2		
B3	1	0.36	20.1	-	-	54.8 (1)	-	3.7	6.6	40.0	100.1 (307)	
	2	0.36	19.9	35.3	45.5	56.0	64.8	3.4	-	40.0		
	3	0.36	20.1	35.1	44.4	52.7	65.2	3.4	-	38.8		
	4	0.36	19.9	34.2	45.5	53.9	63.6	3.2	-	39.6		

(1) Mean compressive strength of three cylinders
(2) Mean flexural strength of two prisms

TABLE 6 CONT'D - PROPERTIES OF HARDENED CONCRETE

Mix no.	Batch no.	W/C	Fly ash, % by wt of cement	Properties of hardened concrete							
				Compressive strength, MPa				Splitting Tensile strength, MPa	Flexural strength, MPa (2)	Modulus of elasticity, GPa	Durability factor, % (Number of cycles)
				1-d	7-d	28-d	91-d				
84	1	0.45	30.2	-	-	42.9 ⁽¹⁾	-	5.5	35.6	98.9 (301)	
	2	0.45	30.2	24.3	34.0	41.5	51.8	-	34.6		
	3	0.45	30.2	24.3	33.3	42.3	50.7	-	35.8		
	4	0.45	30.2	23.0	34.2	43.3	50.7	-	35.6		
85	1	0.41	30.3	-	-	44.4 ⁽¹⁾	-	5.6	38.6	101.5 (313)	
	2	0.41	30.1	27.6	36.8	43.4	56.1	-	36.9		
	3	0.41	30.1	29.2	37.8	45.2	56.1	-	38.6		
	4	0.41	30.3	27.1	37.8	47.1	56.8	-	38.6		
86	1	0.36	30.3	-	-	53.1 ⁽¹⁾	-	6.1	38.6	100.2 (333)	
	2	0.36	30.3	33.8	43.0	51.8	62.3	-	37.8		
	3	0.36	30.3	33.3	43.4	52.2	62.1	-	37.9		
	4	0.36	30.3	33.5	44.2	53.9	62.8	-	38.1		
87	1	0.45	40.0	-	-	42.6 ⁽¹⁾	-	5.2	35.6	101.8 (328)	
	2	0.45	40.0	23.4	32.8	44.1	-	-	35.3		
	3	0.45	40.0	23.4	33.0	41.9	53.0	-	35.6		
	4	0.45	40.0	23.1	33.9	43.9	54.1	-	36.0		
88	1	0.41	40.0	-	-	46.0 ⁽¹⁾	-	5.5	36.6	99.4 (321)	
	2	0.41	40.0	28.2	37.9	46.4	57.3	-	36.0		
	3	0.41	40.0	25.9	36.7	43.6	55.1	-	36.5		
	4	0.41	40.0	26.8	37.2	44.2	54.6	-	36.0		
89	1	0.36	40.0	-	-	58.5 ⁽¹⁾	-	7.3	39.4	99.9 (314)	
	2	0.36	40.0	37.4	47.1	56.7	68.7	-	38.6		
	3	0.36	40.0	35.2	46.3	54.2	65.7	-	37.6		
	4	0.36	40.0	5.5	45.7	58.8	65.0	-	39.4		

(1) Mean compressive strength of three cylinders

(2) Mean flexural strength of two prisms

TABLE 7 - PROPERTIES OF HARDENED CONCRETE - AIR VOID SYSTEM.
(LINEAR TRAVERSE)

Mix no.	Air voids, %	Spacing factor (1)	Specific surface (2)
A1	1.5	0.012	760
A2	2.3	0.017	418
A3	3.5	0.020	295
B1	2.0	0.016	518
B2	3.1	0.014	447
B3	1.4	0.006	1249
B4	2.2	0.007	898
B5	2.3	0.005	1440
B6	2.2	0.006	1140
B7	3.0	0.004	1563
B8	2.1	0.004	1880
B9	2.1	0.004	1590

- (1) To meet ASTM C457, the spacing factor, $\bar{L}$, must be lower than 0.008.
(2) To meet ASTM C457, the specific surface must be higher than 700.

TABLE 8 - COMPRESSIVE STRENGTH - f'_c (MPa)

Time days	Fly ash, % by wt of cement	Water-to-cement ratio		
		0.45	0.40	0.35
1	0	22.9	29.2	35.0
	20	23.8	28.2	34.9
	30	23.9	28.0	33.5
	40	23.3	27.0	36.0
7	0	32.1	39.1	45.2
	20	33.5	36.6	45.1
	30	33.8	37.5	43.5
	40	33.2	37.3	46.4
28	0	40.3	46.6	54.4
	20	41.2	45.3	54.5
	30	42.6	44.8	52.9
	40	43.0	45.4	57.6
91	0	45.5	52.2	61.1
	20	49.0	52.8	64.5
	30	51.1	56.3	62.4
	40	53.6	55.7	66.5

TABLE 9 - MODULUS OF ELASTICITY AT 28-DAYS(GPa)

Fly ash, % by wt of cement	Water-to-cement ratio		
	0.45	0.40	0.35
0	33.7	36.9	38.4
20	35.2	37.4	39.6
30	35.4	38.2	38.1
40	35.6	36.3	38.8

TABLE 10 - SPLITTING TENSILE STRENGTH AT 28-DAYS(MPa)

Fly ash, % by wt of cement	Water-to-cement ratio		
	0.45	0.40	0.35
0	2.7	3.2	3.5
20	2.9	3.1	3.4
30	3.2	3.4	3.8
40	3.4	3.3	3.9

TABLE 11 - FLEXURAL STRENGTH AT 14-DAYS(MPa)

Fly ash, % by wt of cement	Water-to-cement ratio		
	0.45	0.40	0.35
0	4.9	5.7	6.9
20	5.0	4.8	6.6
30	5.5	5.6	6.1
40	5.2	5.5	7.3

COMPRESSIVE STRENGTH AS % OF REFERENCE AT

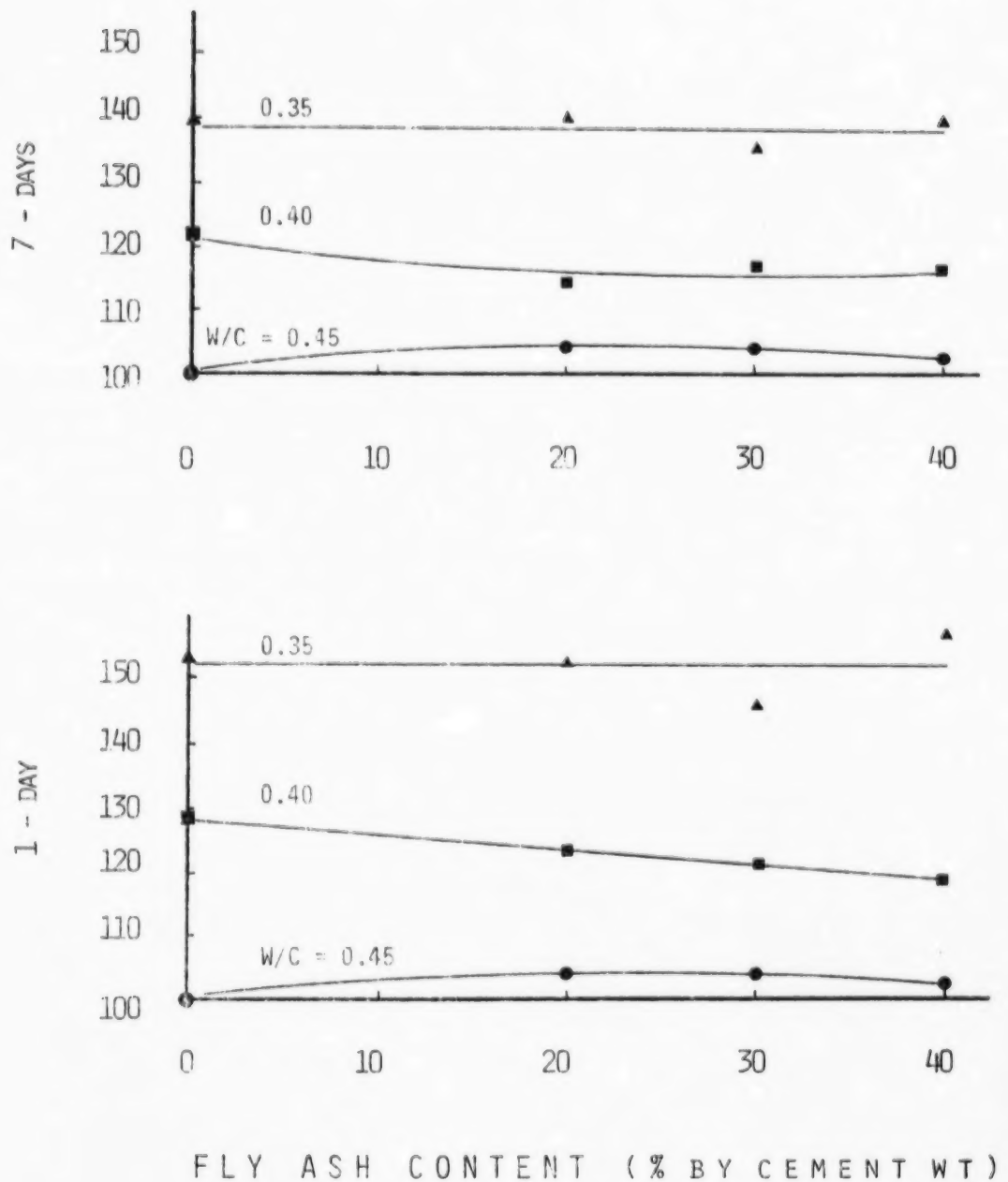


FIGURE 1 A. COMPRESSIVE STRENGTH AS % OF REFERENCE AT 1 AND 7 DAYS VERSUS THE FLY ASH CONTENT

COMPRESSIVE STRENGTH AS % OF REFERENCE AT

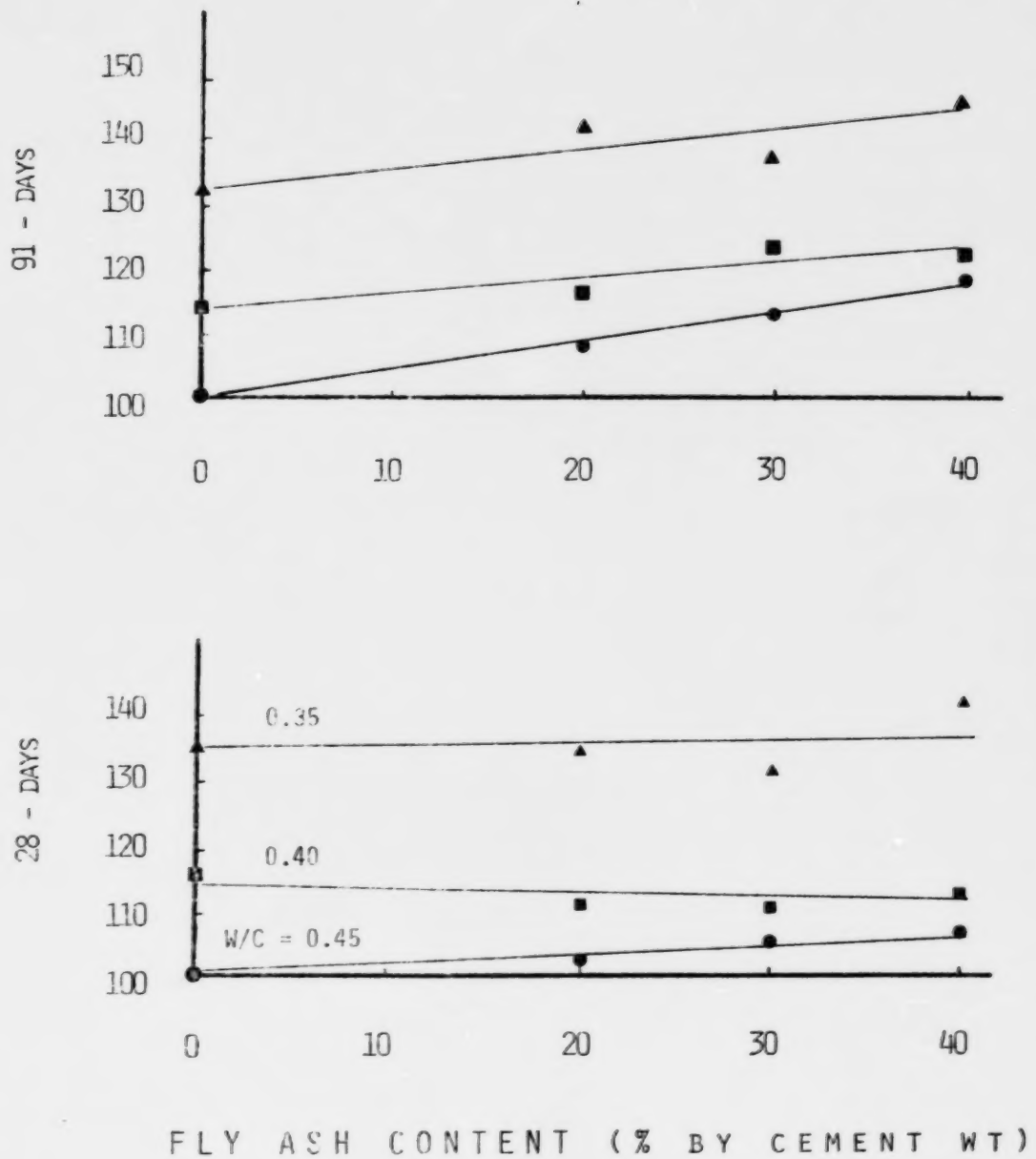


FIGURE 1B. COMPRESSIVE STRENGTH AS % OF REFERENCE AT 28 AND 91 DAYS VERSUS THE FLY ASH CONTENT

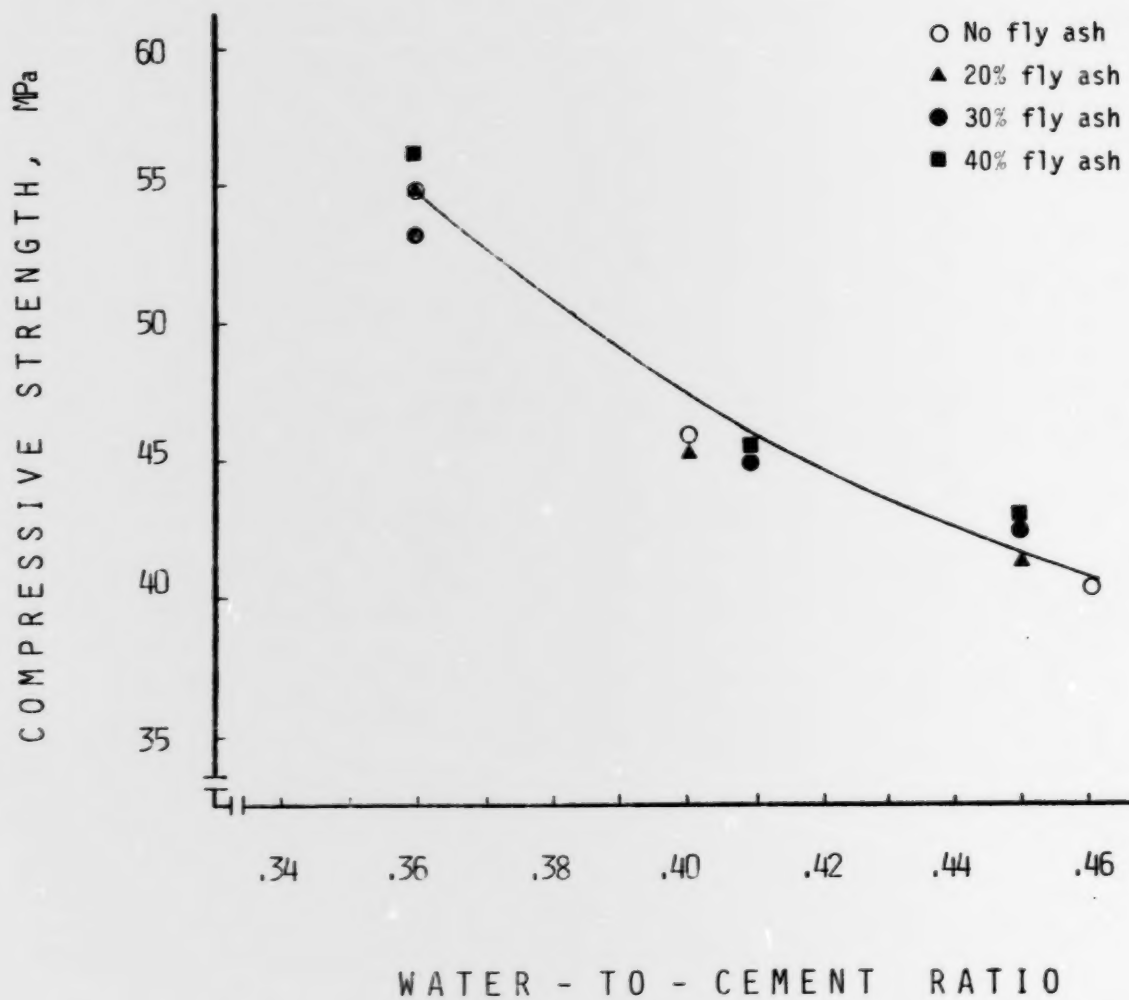


FIGURE 2. COMPRESSIVE STRENGTH AT 28-DAYS VERSUS THE WATER-TO-CEMENT RATIO